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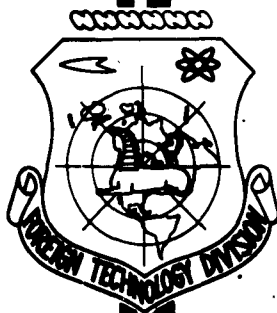
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## FOREIGN TECHNOLOGY DIVISION

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## EFFECT OF DIFFUSION FACTORS ON FLAME STABILITY

V. N. Iyevlev and S. A. Gol'denberg

This article considers the causes for the deviation from the universal relationship of experimental values of critical velocities of flame blow-off from small stabilizers [1, 2]. The experimental investigation was carried out with a gasoline-air mixture using conical and cylindrical stabilizers.

Certain anomalous phenomena were detected when carrying out certain experimental investigations into flame stabilization with poorly streamlined bodies and when elucidating the dependence of the flame blow-off velocity from stabilizers on the fuel mixture composition.

For example, as early as in William's study [3], a disconformity of the position of curves of flame blow-off velocity and the curve of normal flame velocity was established (as a function of the fuel mixture composition or excess air ratio), which was especially evident in the region of maximum values of these velocities. The data derived in these studies were not governed by the universal relationship

$$\frac{u_d}{v} = K \left( \frac{u_d d^2}{a} \right). \quad (1)$$

This type of unconformity, which was observed in the studies mentioned, could not be explained by the experimental errors.

Therefore, the task of this experimental investigation was to elaborate the described phenomenon on small stabilizers, conical and cylindrical rods.

The experiments were carried out with a gasoline-air mixture. The stabilizers were installed along the flow axis of the fuel mixture at a distance of 5 mm from the nozzle of the burner, a tube 32 mm in diameter. We used cylindrical (rod  $d = 4$  mm) and conical ( $d = 5$  mm) stabilizers. As a result of the experiments we obtained values for the flame blow-off velocity as a function of the fuel-mixture composition (excess air ratio  $\alpha$ ).

It was revealed from the experiments that the blow-off velocity  $w$ , as compared with the curve of normal flame propagation velocity  $u_n$ , shifts toward the side of rich mixtures: the peak of the blow-off curve lies at  $\alpha = 0.7$ , and the peak of the curve  $u_n$ , at  $\alpha \approx 0.9$ . When using other fuels, the peak can shift toward lean mixtures. The latter was observed in experiments with methane-air mixtures [6]: the peak of the blow-off curve was at  $\alpha \approx 1.1$ , and the peak of the normal flame velocity at  $\alpha \approx 0.95$ .

The shift of the peak of the blow-off curves [3, 4] has been explained by the difference in the numerical values of the diffusion coefficient of fuel  $D$  and the coefficient of thermal diffusivity of the mixture  $a$ . The latter coefficient for air mixtures of hydrocarbons is for all practical purposes determined by the thermal diffusivity of air, where for gasoline  $D < a$ , and for methane  $D > a$ .

The most direct method of elucidating the role of molecular diffusion in the flame stabilization process is, evidently, a study of the composition of combustion products and their temperature in the circulation zone behind the stabilizer.

Corresponding experiments were carried out on a conical stabilizer ( $d = 7 \text{ mm}$ ) and a longitudinally streamlined rod ( $d = 4 \text{ mm}$ ).

The combustion products were gathered from the core of the circulation zone close to the end of the stabilizer by means of a thin medical needle with an outside diameter of 1 mm. The needle was soldered into the air-cooling tube. The temperature in the circulation zone was determined by the sodium-line reversal method.

**TABLE 1**

Excess Air Ratio (Initial Mixture and Beyond the Stabilizer) and Composition of Combustion Products in Circulation Zone

$\alpha$ of initial mixture	Composition of combustion products, %							Type of stabilizer
	CO <sub>2</sub>	CO	CH <sub>4</sub>	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>	$\alpha$ analysis	
0,60	12,5	3,2	0,5	3,2	0,2	80,4	0,91	rod
0,70	12,2	2,0	0,6	2,2	0,3	82,7	1,00	$d = 4 \text{ mm}$
0,80	11,8	1,5	0,3	3,4	0,1	82,9	1,10	"
0,90	11,2	0,7	0,1	4,7	0,0	83,3	1,23	"
0,65	7,9	10,8	4,2	0,3	0,4	76,4	0,65	cone
0,70	9,0	8,7	2,6	0,2	0,5	79,0	0,71	$d = 5 \text{ mm}$
0,80	11,0	6,0	1,8	0,3	0,2	80,7	0,79	"
1,00	12,4	1,5	0,3	2,0	0,1	83,7	1,02	"

We see from Table 1 that the excess air ratio calculated from the analysis of the combustion products in the circulation zone beyond the rod ( $d = 4 \text{ mm}$ ) differs appreciably from  $\alpha$  of the initial mixture. This difference was not observed in the case of the conical stabilizer ( $d = 5 \text{ mm}$ ).

If the data on the blow-off velocity at the rod ( $d = 4 \text{ mm}$ ) is plotted on a graph in relation to the true values of  $\alpha$  in the circulation zone (Fig. 1), the blow-off curve is shifted to the right and will occupy a position (dashed line) corresponding to the position of the curve of normal flame velocity. In this case the peaks of both curves will be in the region  $\alpha = 0.9 - 0.93$ . Similar data for the



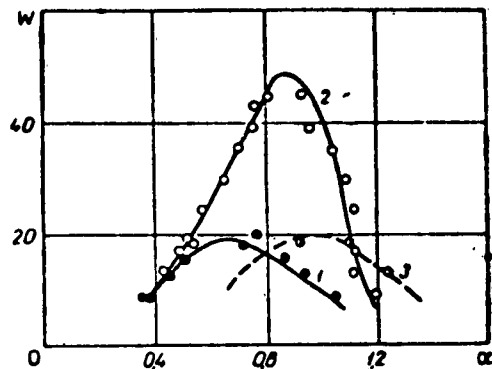


Fig. 1. Dependence of blow-off velocity  $w$  (m/sec) on excess air ratio  $\alpha$  of the initial mixture: 1) for rod  $d = 4$  mm; 2) for conical stabilizer  $d = 5$  mm; 3) on the excess air ratio in the circulation zone for rod  $d = 4$  mm.

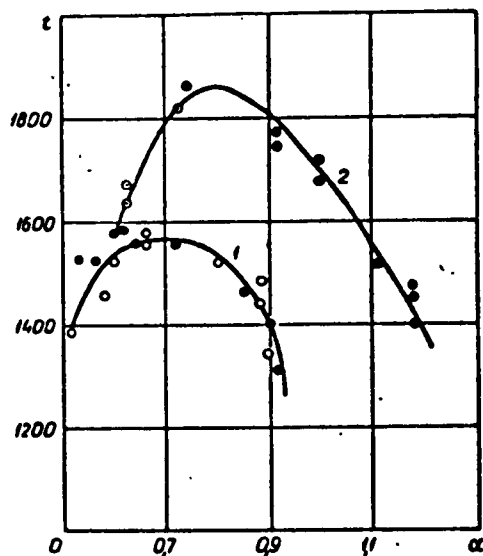


Fig. 2. Dependence of temperature in circulation zone  $t$  (°C) on the excess air ratio  $\alpha$ : 1) for rod  $d = 4$  mm (the curve is plotted in conformity with the characteristic of the initial mixture); 2) for conical stabilizer  $d = 5$  mm.

conical stabilizer ( $d = 5$  mm) did not yield a divergence between  $\alpha$  of the initial mixture and  $\alpha$  of the combustion products in the circulation zone, and therefore shifts of the curves of blow-off velocity are not revealed.

In addition to determining the composition of the combustion products in the circulation zone beyond the rod ( $d = 4$  mm) and conical stabilizer ( $d = 5$  mm), we measured the temperature.

TABLE 2

Results of Temperature Measurements in the Circulation Zone

x of initial mixture	Composition of combustion products, %							t°C by anal-	t°C meas-	$n_1$	$n_2$	$\frac{n_2}{n_1}$	type stabilizer
	CO <sub>2</sub>	CO	CH <sub>4</sub>	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>	$\alpha$ analysis	ysis	ured				
0,9	11,2	0,8	0,0	4,8	0,0	83,2	1,23	1630	1580	0,084	0,062	0,74	rod $d=4$ mm cone $d=5$ mm
0,9	9,3	5,7	1,4	2,5	0,3	80,8	0,91	1800	1850	0,084	0,087	1,03	

We see from Table 2 that the temperature values in the circulation zone calculated by analyzing the combustion products are close to those directly measured.

Temperature curves are plotted in Fig. 2 for the rod  $d = 4$  mm and conical stabilizer  $d = 5$  mm.

From a comparison of Figs. 1 and 2 we see that the position of the peaks on the temperature curves corresponds to the curves of blow-off velocity. Evidently, if we assume for the basic characteristic the true composition of the combustion products  $\alpha$  in the circulation zone of the rod, the temperature curve for it will be shifted to the right and the peak of the curve is at a point corresponding to  $\alpha \approx 0.9$ .

Thus, direct measurements show that in the circulation zone beyond the rod  $d = 4$  mm, the composition of the combustion products changes, the nitrogen content increases in them, and owing to this the

temperature drops. In this case the composition of the combustion products after total combustion and their temperature correspond to the combustion products obtained on ignition of the initial mixture  $\alpha = 1.23$ .

In Table 2 this is illustrated by the magnitudes of  $n_1$  and  $n_2$  which are the ratio of the number of carbon atoms to the number of nitrogen atoms in the initial mixture ( $n_1$ ) at  $\alpha \approx 0.9$  and in the circulation zone  $n_2$ . In the case of the conical stabilizer  $d = 5$  mm, when no shift of the curves to the right is observed, the ratio  $n_2 : n_1 = 1$ . In the case of rod  $d = 4$  mm where there is a shift of the blow-off curves and the composition of the combustion product ( $\alpha_{\text{anal}} = 1.25$ ) in the circulation zone does not correspond to the initial mixture, the ratio is  $n_2 : n_1 < 1$ .

The described phenomena associated with the effect of molecular diffusion under specific conditions of flame stabilization were noted in works on small stabilizers [6].

A change in the composition of combustion products in the circulation zone beyond the small stabilizer and also a change of their temperature in comparison with the initial mixture leads to a change in the intensity of the chemical source at the interface of the fresh mixture flow and the circulating heated combustion products. Therefore, in these cases the use of the value of  $u_n$  for calculations is not substantiated, it should be specially calculated. However, the method for such a calculation has still not been developed.

Numerous calculations show that a sufficiently good generalization of experimental data on blow-off from small stabilizers can be obtained if we artificially combine with respect to  $\alpha$  the curves of blow-off velocity with the curves of normal flame velocity or with blow-off curves obtained on large stabilizers (Fig. 1).

The certain possible error in this case is associated with the fact that the blow-off velocity curves should be shifted not only with respect to  $\alpha$  but also with respect to temperature. This is due to dilution of the mixture in the circulation zone as a result of diffusion of nitrogen (air) from the initial cold mixture.

The authors express their sincere thanks to L. N. Khitrin, corresponding member of the USSR Academy of Sciences for his very valuable help in carrying out the study.

#### DESIGNATIONS

$w$  is the flow velocity at which flame blow-off occurs;  $d$  is a determining dimension;  $u_n$  is the normal flame velocity;  $\nu$  is the kinematic viscosity;  $a$  is the coefficient of thermal diffusivity;  $K$  is a constant.

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HEAT EXCHANGE IN THE HORIZONTAL SURFACES OF  
HEAT INSULATING STRUCTURES SLOTTED  
WITH METAL IN DEEP COOLING  
SYSTEMS

N. V. Krylov and K. I. Strakhovich

Heat exchange in the horizontal surfaces of heat insulating structures slotted with metallic structures in systems of deep cooling is experimentally investigated. The values of coefficient of heat exchange obtained are compared with its calculated values derived by various means.

In number of problems of contemporary heat technology and cryogenics it is necessary to determine the heat exchange on the surface of different types of the heat insulating setups slotted with metal structures. The existent formulas for determining the coefficient of heat exchange for horizontal and vertical walls and cylindrical surfaces under conditions of natural convection give values for this coefficient which are very different from actuality, especially at low temperatures [1, 3].

This is explained by the fact that a purely statistical approach to the problem of determining  $\alpha$  adopted for the case

of an insulating structure slotted with metal does not correspond to the actual picture, since the temperature gradient sharply increases above the surface of the metal occupying a relatively small area in the whole contact surface of the examined insulating structure with air or cold gas; and this creates a corresponding temperature pressure in the contiguous air (gas) layer and by that very fact damages the purely statistical conditions of heat exchange via the given layer of air (gas).

Hence the necessity arises of investigating the distribution of the air and cold gas temperatures above the insulating surface and above the surface of the metal in order to obtain more exact values for coefficient of heat exchange  $\alpha$ .

The experimental arrangement used in the present work was a metal Dewar vessel of diameter  $\underline{d} = 250$  and of height  $\underline{h} = 600$  mm (Fig. 1). Into this vessel was put a laboratory specimen of the insulating structure in the shape of a cylinder ( $\underline{b} = 200$ ,  $\underline{h} = 200$  mm) which was filled with the insulant intersected with "heat bridges" (metal). These heat bridges were made of various materials and were of different construction.

Depending on the requirements of the experiment the heat bridge of a respected material either was supported from both the hot and cold side on steel disks (diameter  $\underline{d} = 200$  mm and thickness  $\delta = 15$  mm) imitating heat barriers, or merely cut through the insulation without heat barriers. Loose insulation (Mipor, aerogel, and slag cotton), was utilized. When the liquid nitrogen poured into the Dewar vessel reached a certain level and when the temperatures throughout the vessel and the insulation surrounding it had been distributed in a constant manner, the experimental specimen was

fixed in the vessel supported on stops welded to the internal walls of the vessel. The vessel meanwhile was fastened in a hollow steel cylinder on a light stand and the clearance between its external surface and the inner steel cylinder was packed with insulation in order to decrease the heat currents from the surrounding medium to the liquid nitrogen.

In order to determine the temperatures in the mass of insulation along the heat bridge and also the temperatures of the air bathing the upper surface of the specimen, and also of the cold gas bathing the lower surface of the specimen, we attached copper-constantan thermocouples with a wire diameter  $d = 0.2$  mm (Fig. 2).

The thermocouples were led out to a multipoint switch connected with a laboratory potentiometer for accurate measurements of the emf. The zero point was secured by placing the warm junctions in a glass Dewar vessel filled with crushed ice and distilled water.

The control indices were taken off until a stationary regime was reached. Confirmation of this was the constancy of the emf values in the respective points.

From processing the experimental data temperature distributions through the air and cold gas above the surface and insulation and the heat bridges were obtained as a function of the material from which the heat bridges were made, of their construction, and of the methods of insulating them from the surrounding medium and heat barriers (Fig. 2). The adduced data show that in a definite area of the air at a height of about 20 to 40 millimeters of the heat barrier (insulation) and 1 to 25 millimeters above the surface of the heat bridges, whether or not projecting on heat barriers, there is observed a substantial difference in the temperature

distribution. Above the indicated region the same air temperature distribution takes place for all the examined types of insulating mechanisms.

Table 1 shows the relative values of heat coefficients  $\alpha$  calculated by various methods for the heat insulating structure slotted with heat bridges constructed as shown in Fig. 2 and made of copper and 1Kh18N9T steel.

For heat insulating structures traversed by the other metals used in the investigation, the values of the coefficients of heat exchange lie within the limits indicated in Table 1, the change in  $\alpha$  occurring in direct dependence on the heat conductivity of the metal and insulation.

The difference in the coefficients of heat exchange  $\alpha$  from air to metal calculated by the indicated methods is explained by the fact that because of the slight thickness of the boundary layer it is very difficult to measure that thickness exactly; the coefficients of heat exchange  $\alpha$ , however, experimentally obtained and also obtained by calculating the heat currents along the thermo elements, differ one from another within limits permissible in our calculation.

The increase in the velocity of air movement on the warm side of the insulation structure caused by a substantial temperature change evidently explains the nonconformity of the experimental values of the coefficients of heat exchange  $\alpha$  with their calculated values obtained from extent formulas.

The value of the coefficient heat exchange from the metal to the cold gas is higher in comparison with its value from air to metal. This is explained by the formation of a vapor resulting



from the evaporation of the liquid nitrogen and filled with the tiniest droplets of liquid whose contact with the warm surface of the metal leads to vigorous vaporization strengthening the heat exchange, and consequently also to increasing the coefficient of heat exchange  $\alpha$  from metal to cold gas.

The values of  $\alpha$  from air to insulation and from insulation to cold gas, based on experimental data and determining the heat currents along the elements of the insulating structure, satisfactorily agree, but differ greatly from the values calculated from the extant and empirical formulas.

This considerable deviation is connected with the fact that above the insulation we observe air stagnation, confirmed by approximate calculation of the velocity of air motion (0.22 to 0.26 m/sec. above the metal surface), but the ratio of the velocity of air motion above the metal  $u_1$  and above the insulation  $u_2$  is  $u_1/u_2 = 20-30$ . It is obvious that at such small velocities their inconsiderable change leads to a noticeable change in coefficient  $\alpha$ ; and it is necessary to keep this in mind when solving practical problems.

TABLE 1

Relative values of coefficients of heat exchange for heat insulating structures traversed with heat bridges.

Metal	Heat-exchange conditions	Coefficient of heat exchange ( $\text{kcal/m}^2\text{-deg-c}$ )						
		Data from the experiment	Data calculated from thermal currents through thermal elements of the insulating structure	Empirical and semi-empirical formulas of various authors				
				From Griffith-Davis formula	Henke formula	Bosworth formula	Mikhelav and Kutateladze data	Joukowski formula
Copper	air to metal	12,800	14,600	7.13	9.30	10.60	10.80	10,3500
	metal to cold gas	—	25,200	3.31	8.20	7.10	6.80	6,7800
	air to insulation	0.322	0.300	6.05	7.92	8.15	9.10	9,0500
	insulation to cold gas	0.355	0.378	2.71	6.72	5.60	6.85	0,0875
1Kh18N9T Steel	air to metal	4,300	5,600	6.24	8.12	8.40	9.20	9,3000
	metal to cold gas	6,600	9,850	2.84	7.05	7.10	6.80	2,4600
	air to insulation	0.360	0.380	5.54	7.34	7.65	8.10	8,3200
	insulation to cold gas	0.340	0.370	2.39	5.92	4.15	6.00	—0,4500

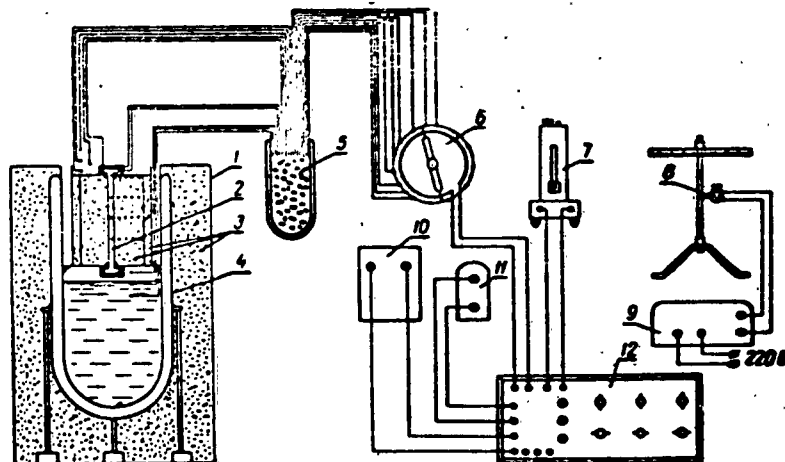


Fig. 1. Diagram of experimental setup.  
 1) Steel cylinder, 2) specimen under investigation, 3) insulation, 4) metal Dewar vessel, 5) Dewar vessel for thermocouple warm junctions, 6) multipoint switch, 7) mirror galvanometer, 8) metering device, 9) power source, 10) battery of galvanic cells, 11) normal Weston cell, 12) potentiometer Weston.

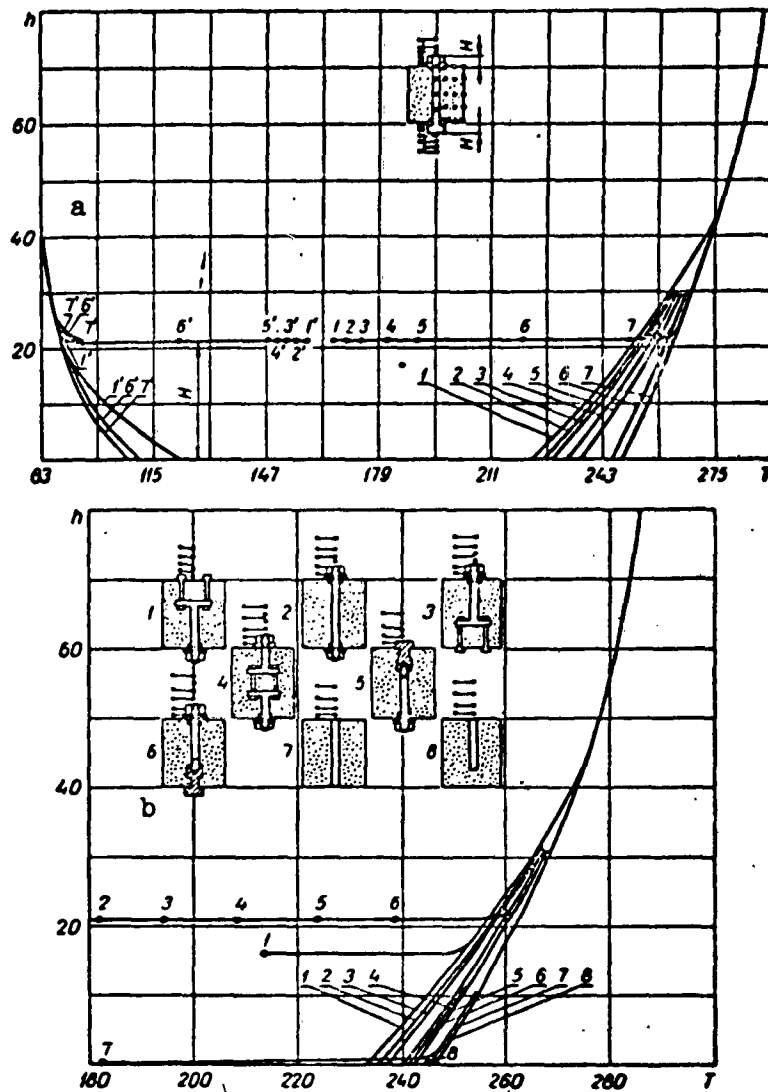


Fig. 2. Change in temperature of air and cold gas close to horizontal surface of insulation (Mipor) and of heat bridges: a) different materials in heat bridges of the same construction: air side (1-7); cold gas side (1'-7'); horizontals (1-7 and 1'-7') are temperatures of projecting surfaces of heat bridges of copper (1, 1'); aluminum (2, 2'); duraluminum [3-5% Cu] (3, 3'); brass [70% Cu, 30% Zn] (4, 4'); carbon steel [0.01% C] (5, 5'); stainless steel [1Kh18N9T] (6, 6'); textolite, goethinax (7, 7'). (b and c continued on next page).

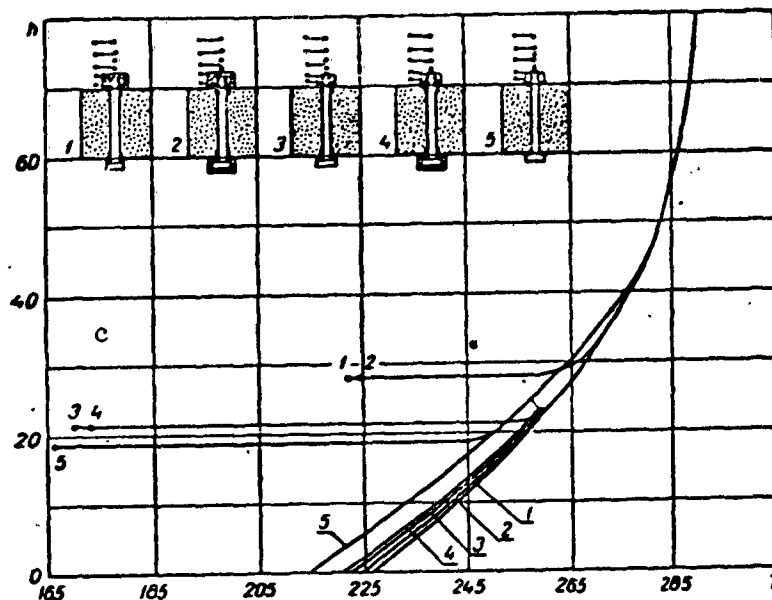


Fig. 2 (continued). b) Different heat bridge structures of the same material (carbon steel) on the air side: 1-8) types of heat bridges, the temperature on the projections of which is shown by the corresponding numbers on the horizontals. c) Different insulation structures at the ends of heat bridges all of the same material: 1-5) types of insulating structures, the temperature on the projections of which is shown by the corresponding numbers on the horizontals.

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